Mission Activity Planning for Humans and Robots on the Moon

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Abstract

A series of studies is conducted to develop a systematic approach to optimizing—both in terms of the distribution and scheduling of tasks—scenarios in which astronauts and robots accomplish a group of activities on the Moon, given an objective function (OF) and specific resources and constraints. An automated planning tool is developed as a key element of this optimization system.

For the first two studies, astronaut safety is given foremost priority, and the automated planner's primary OF is minimizing the amount of time spent in extravehicular activity (EVA), with minimization of intravehicular activity (IVA) as a secondary OF. This is accomplished through the use of a robot, teleoperated from Earth, which relieves the astronauts of some of the work.

For the third study, currently in progress, the OF is revised to maximize scientific productivity, achieved by having astronaut geologists work the *most* EVA hours that are deemed consistent with safety. Minimizing the robot's idle time, when it wastes power waiting for the astronauts to enable its next activity, becomes an additional element of the OF. A much more complex scenario is developed for a better demonstration of the value of an automated planner.

1. Introduction

NASA's Vision for Space Exploration [1] calls for returning astronauts to the Moon in preparation for human missions to Mars and beyond. On the Moon, astronauts would gain experience in using local resources (e.g., lunar soil and lunar water ice if it exists) and in working with robots and other equipment to accomplish their tasks.

The Directorate Integration Office of NASA's Exploration Systems Mission Directorate asked the START (Strategic Assessment of Risk and Technology) team [2] at NASA's Jet Propulsion Laboratory (JPL) to develop and apply a system for optimizing scenarios in which astronauts and robots accomplish a group of activities on the Moon, given certain resources and constraints. Many of the large-scale planners discussed in the

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literature focus primarily on scheduling activities with predetermined assignments to agents, tools, etc. [3] The START approach considers alternative assignments of agents, tools, etc. as well as time sequencing of activities.

We are currently conducting the third in an ongoing series of studies which provide a good illustration of the iterative nature of the process. The results of any given study can enhance the decision-makers' understanding of the problem they want to solve, leading them to modify their inputs for the next study. As the series of studies progresses, the model they address increasingly improves. As a consequence of this dynamic in the human-robot studies, both the optimization system and the mission scenarios have been evolving and the ground rules differ from study to study. However, certain characteristics are common to all of the studies so far:

1.1 Overall problem statement

Given a set of tasks to be accomplished and a set of agents, tools and resources, and their support structure, compute an allocation of tasks that would optimize a given figure of merit, subject to given constraints. The result is a timeline showing what tasks are executed, when, and by which agents.

1.2. Approach to solving the problem

1. Identify agents (astronauts and robots), activities (move, carry, deploy, etc.), and resources (tools, vehicles, power, time, etc.).
2. Identify parameters and constraints.
3. Define the figure of merit (FOM) to be optimized.
4. Define the starting configuration state, S (e.g., astronauts in the habitat module, pressurized vehicle docked to the habitat, none of the tasks accomplished, etc.).
5. Define the goal configuration state, G (e.g., all tasks accomplished and astronauts back in the habitat module, etc.)
6. Search for the optimal allocation of tasks to agents and the optimal sequence of events, given the figure of merit (aka objective function) and all appropriate constraints.
    a. Starting from S, generate all the new possible configurations (subject to pruning techniques that expedite progress toward the optimal solution).
    b. Evaluate each new configuration using FOM. Select the best alternative that does not violate any constraint.
    c. Repeat until G is reached. This process generates a tree. The optimal task allocation and associated information are given by the path between S and G.

1.3. Information structure

The various information components, which are defined by the user, are described in a hierarchical structure, such as in the example given in Fig. 1.

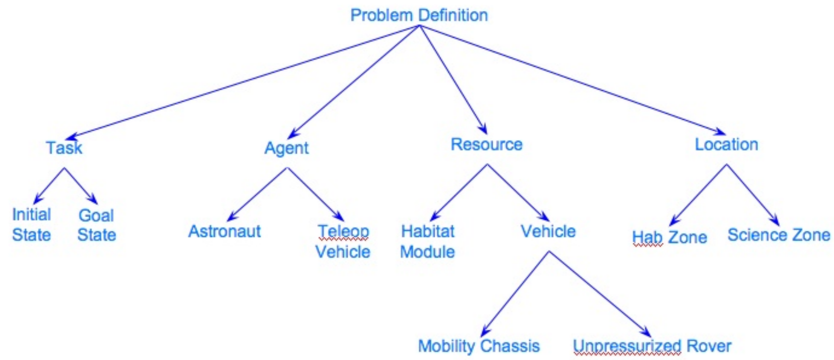

Figure 1. Subset of the information structure

1.4. Rapidly expanding search space

Even with the relatively uncomplicated problems considered in the first two studies, the number of possible combinations of agents, resources, and activities led to a large number of nodes to be explored, as illustrated in Fig. 2. Heuristics ("rules of thumb" to guide the choices of the planner algorithm) needed to be developed to enable the planner to reach its solution in a manageable amount of time.

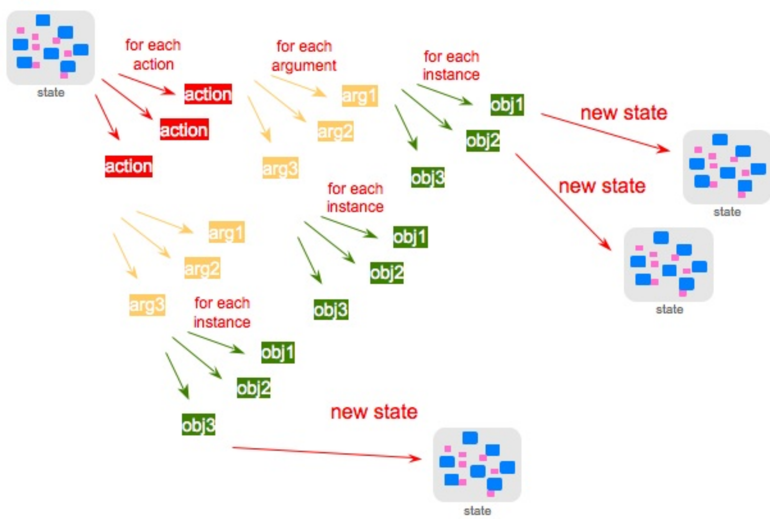

Figure 2. Illustration of rapidly expanding search space

2. First study

The first study addressed the planning of one day of science tasks that would be part of a 60-day mission. The agents were defined as 2 astronauts and an unpressurized rover (UPR), i.e., a robotic chassis that is teleoperated from Earth. The resources available to these agents were the following:

- a small, pressurized rover (SPR) consisting of a pressurized cabin mounted onto a mobile chassis, which would enable astronauts to travel across the lunar surface without the encumbrance of space suits.
- a habitat module, in which the astronauts would live while on the lunar surface

- two science packages (arm, tools, sample containers, etc.): one each for the pressurized vehicle and the UPR.

The mission's activities comprised 6 science tasks, identified by NASA's Lunar Architecture Team (LAT) [4], to be performed at each of 2 science zones on the lunar surface: collect rock samples, conduct geological context survey, collect rake sample, collect soil sample, collect drive-tube sample, drill and collect a core sample.

The activities were divided into their component actions, each of which was described in detail to enable the algorithm to use the information:

- name of the action (e.g., DRIVE)
- arguments (which entities are involved in the action—e.g., DRIVE (astronaut A1, vehicle V1, location X, location Y)
- preconditions (what must hold for the action to be applicable—e.g., A1 location = V1 location = X)
- Computational steps that encode what the action does (e.g., A1.location :=Y; V1.location :=Y; A1.evatime = A1.evatime + delta)
- Post-conditions (what must hold after the action was carried out—e.g., A1.location = V1.location =Y)

It was assumed that each task could be performed in any of three ways:

- by astronauts working EVA (extravehicular activity—i.e., walking on the lunar surface in pressurized space suits)
- by astronauts working IVA (intravehicular activity—i.e., operating robotic arms and tools from inside the SPR's pressurized cabin)
- by a robot (UPR) teleoperated from Earth

2.1. Parameters and constraints

A table of parameters was compiled, detailing how much time would be required for each activity under each set of circumstances. Other parameters such as likelihood of success, quality of samples collected, etc., were assumed to be equal regardless of whether they were done by EVA, IVA, or teleoperation from Earth.

For example, for purposes of this study, drilling a core sample was said to take 1.75 hours for an astronaut working EVA, 3.5 hours for an astronaut working IVA, and 7.0 hours for the UPR teleoperated from Earth. (EVA times were taken from Apollo data. IVA and Earth-teleoperation times were estimated based on the EVA times, but none of these parameters has yet been validated by independent peer review.)

Constraints were identified which, among other things, limit the amount of time available to the agents. It was determined that each astronaut can perform a maximum of 8 hours of EVA activities per day. Additional time may be spent on IVA activities, but the total of EVA and IVA is not to exceed 16 hours. The pressurized vehicle and the UPR can each perform up to 16 hours before needing to be recharged at the habitat.

For EVA and IVA, it was assumed that the astronauts would be able to set up the core-sampling equipment and leave it to run while they performed other tasks. The UPR would also be able to conduct core sampling, but would have to stay with that task exclusively until it was completed.

2.2. Problem and search

The problem posed was to determine which tasks should be performed by which of these means (astronaut EVA, astronaut IVA, or teleoperated robot) and the optimal sequence of events. At the time of this first study, our sponsor gave highest priority to astronaut safety and directed us to make the objective function minimization of EVA time, since being outside in a space suit is considered to be the most hazardous state for an astronaut. The secondary objective was to minimize IVA time, and in third place was minimizing the amount of time the robot spends working.

We developed a table of starting and goal states and established a heuristic to guide the planning algorithm: As it explored all possible nodes in the search space, the planner was to penalize those which required EVAs and, to a lesser extent, IVAs.

Our planner (called HURON) [5] is based on the A* least-cost search algorithm. Various search techniques, including a hash map, min heap queue, and cycle loop detection, shortened the search rate from as much as one node per second to about 100–200 nodes per second, depending on the computer. A partial graph of the search is shown in Fig. 3.

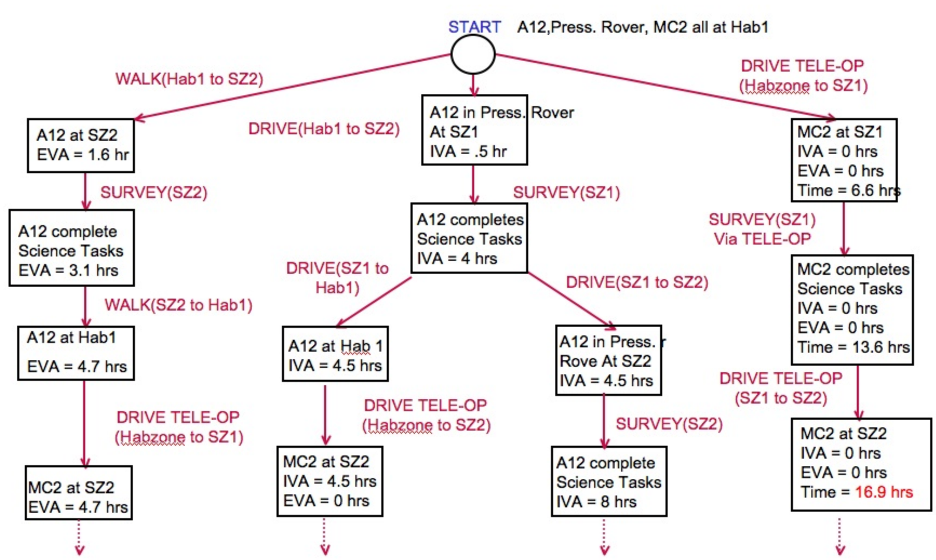

Figure 3. Partial graph of the search. “A12” means “astronauts 1 and 2.” “MC2” (Mobile Chassis 2) was the term used for the UPR during the first study. “SZ” means “science zone.”

We ran the planner with two scenarios: one in which the astronauts do all of the tasks themselves, and one in which the UPR does some of the work. For each scenario, HURON generated an Excel spreadsheet showing a timeline of the optimal activity plan, with actions for each entity placed on the timeline.

2.3. Results

Since the objective function we were given was to minimize EVA time, the planner calculated that the optimal plan was simply to have the astronauts conduct all of their tasks as IVAs, without ever donning space suits and leaving the relative safety and comfort of a pressurized cabin. While avoidance of all EVA activity is not what was ultimately desired, this common-sense result validated the planner, which had to search a fairly extensive trade space to find its solution.

In the first scenario, as previously mentioned, the astronauts performed all of the tasks. In the second scenario, they performed all 6 tasks at the first science zone while the UPR performed 3 tasks in the second science zone, after which the robot needed to return to the habitat to recharge its batteries. Upon completing their work at the first science zone, therefore, the astronauts drove to the second science zone and conducted the three tasks that the UPR had left undone. The tasks that the UPR completed saved 1.5 hours of astronaut IVA time when compared to the scenario in which the astronauts did all of the work.

3. Second study

In recognition of the value to science of having astronaut geologists walking on the lunar surface and directly observing the rocks and landscape, most tasks were mandated to be done as EVAs in the second study. The sponsors instructed us that, for purposes of this study, the pressurized vehicle would not have a robotic arm, and therefore no IVAs would be possible. Further, the UPR in this study would be equipped only for drilling core samples. However, safety was still given foremost priority, and so the objective function remained minimizing EVA time.

Instead of traveling to Science Zone 2 while the astronauts drove to Science Zone 1 as in the first study, the UPR in this study would simply follow the astronauts to each of the two science zones, drastically reducing the need for the Earth-based teleoperators to painstakingly keep the robot from running into trouble. The astronauts would perform the geological surveys that are needed to determine where to collect the core samples, and would place marker beacons on the lunar surface to tell the UPR where to set up its drill. Without the need to find its own drilling locations, the time required for UPR drilling was dramatically reduced to equal the 1.75 hours the astronauts would require, working EVA, to perform the same task. (As in the first study, the parameter values in this study have not yet been validated by independent peer review.)

Other parameters were changed as well. Total allowable astronaut work time was reduced to 15 hours, of which no more than 8 could be EVA. And the astronauts would no longer be allowed to multitask. Unlike the first scenario, they would not be able to set up the core-drilling operation, leave it to operate while they performed other tasks, and then return to it for completion.

This study compared a scenario in which the astronauts perform all tasks with a scenario in which the UPR conducts the core-drilling activity at both science zones and carries the cores back to the habitat for the astronauts to unload. While the study simplified many aspects of the mission, it also introduced one area of complexity: temporal dependencies. The UPR could not drill until after the astronauts placed their marker beacons. The astronauts could not unload the core samples until both the astronauts and the UPR had returned to the habitat. For the first time, the planner would need to synchronize schedules.

3.1. Results

The results were displayed as a timeline, a portion of which appears in Fig. 4.

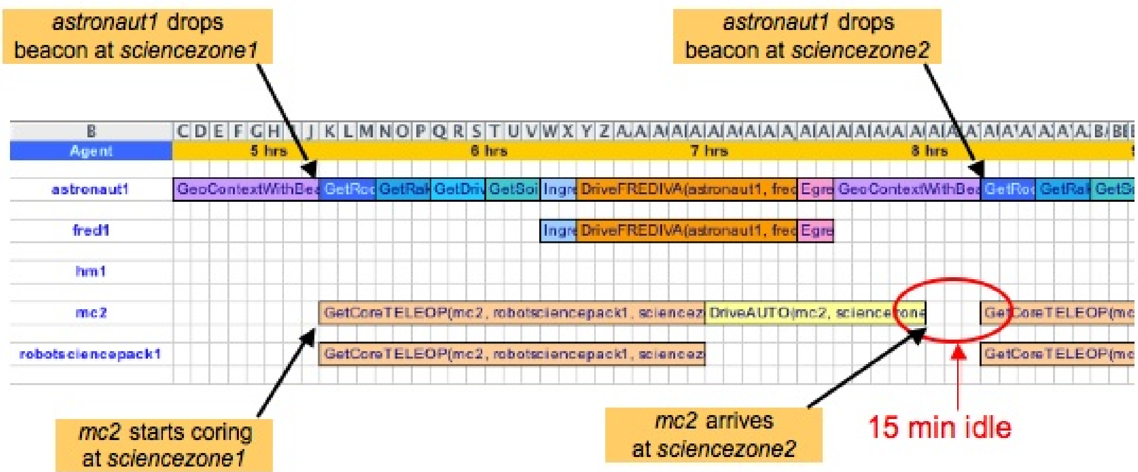

Figure 4. Portion of the timeline of astronaut and robot activities. "FRED" was the term used for the SPR at the time of this study.

The second scenario was found to save 1.9 hours of EVA time if the astronauts unload the core samples during the same day, and 3.2 hours of EVA time if the astronauts unload the core samples as the first activity of the next day (1.3 hours of unloading time would be on lien for the next day). However, two gaps appeared in the UPR's timeline, during which it had to stand by and wait for the astronauts to catch up. It was calculated to consume 400 W during this idle time, an undesirable waste of power.

4. Third study

Reviewing the results of the first and second studies led to several realizations which impacted the third study. Most importantly it was agreed that, to maximize the scientific benefit of having astronaut geologists on the lunar surface, the astronauts would be assigned as much EVA time as is consistent with safety, and EVA time would be treated as a constraint rather than a parameter to be minimized. The objective function became maximizing productivity (in terms to be determined).

The third study comprises four versions of one basic mission (see Fig. 5). The number of science zones has grown from 2 to 6, each of which measures 3 km by 3 km, and the tasks to be conducted at each one have increased from 6 to 8, with deployment of seismometers added to the geological-survey and sample-collection tasks. At the first science zone, one more task is required: deployment of a science station.

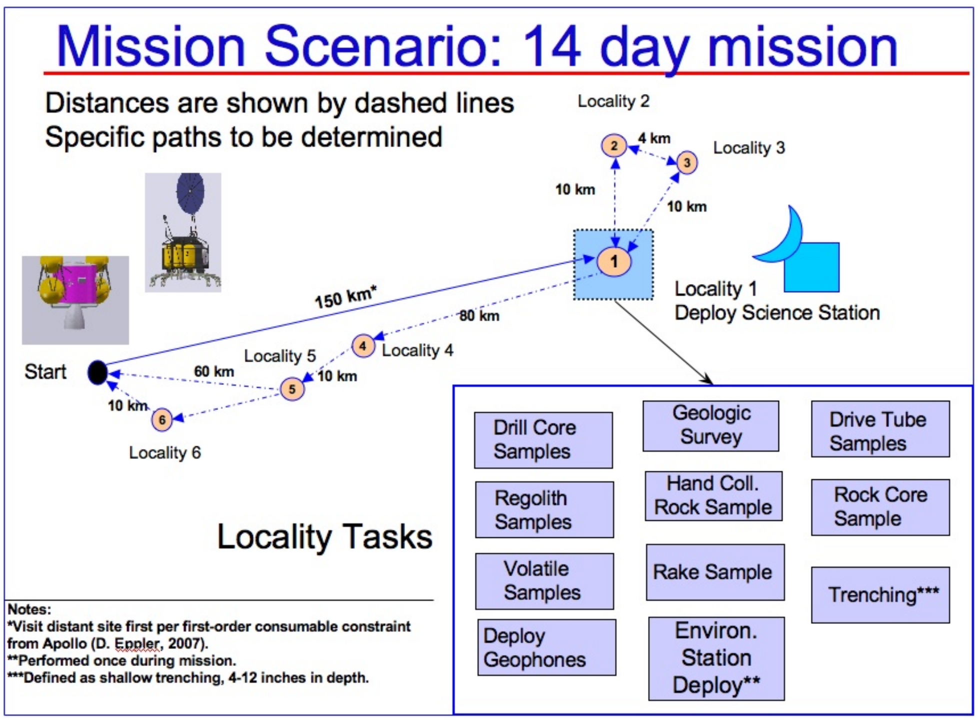

Figure 5. Illustration of one of the versions of the mission considered in Study 3.

Among the four versions of the mission, two are 14-day missions while two are 30-day missions. Two employ a crew of 2; the other two use a crew of 4. One version includes a mobile habitat; the other three involve a stationary habitat to which the astronauts must periodically return. Various combinations of SPR and UPR are being considered, with various combinations of capabilities. All of the vehicles can be driven by the astronauts, teleoperated from Earth, or set to operate autonomously. A breakdown requiring repair will be built into at least one scenario. The final difference among the four versions is the distance the astronauts will travel from the ascent craft, which will ultimately return them to the orbiting spacecraft that will bring them back to Earth. Development and analysis of this study is currently underway.

5. Conclusions

The START team's HURON automated planning tool and the system for using it can be an extremely helpful asset to NASA decision-makers seeking (1) to optimize the distribution of activities between astronauts and robots engaged in scientific pursuits on the lunar surface, and (2) to schedule these activities in the most efficient order. The START approach is independent of any specific problem and gives the user freedom to specify agents, actions, resources, parameters, constraints, start and goal states and the objective function to be optimized. The utility of this planner is evident even in the relatively simple missions considered in the first two studies, and it is essential in the much more complex third study.

The planner is capable of minimizing astronaut EVA and IVA time by assigning work to a robot teleoperated from Earth, as demonstrated by the first two studies, in which astronaut safety was given primary emphasis. However, it became clear in the course of conducting these studies that EVA time is better treated as a fixed constraint to take full advantage of the opportunities presented by having astronaut geologists working in situ on the lunar surface, and that maximization of productivity (in terms still to be determined) makes a better objective function. It also became clear that temporal dependencies between astronauts and robot can lead to power-wasting idle time for the robot, and that minimization of this idle time should become part of the objective function.

In all, this study promises to be an excellent demonstration of the value of a system such as that employed by the START team in optimizing NASA's upcoming activities on the Moon.

6. References

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7. Acknowledgements

The authors greatly appreciate the extensive background information regarding geological survey investigation techniques graciously provided to us by Dean Eppler. Thanks are due to Pam Clark, Ruthan Lewis and Dean Eppler for their input on science goals and techniques; and Andrew Abercromby and Mike Gernhardt who provided much data regarding EVA tasking. We also benefited greatly from the “A Notional Example of Understanding Human Exploration Traverses on the Lunar Surface” by John E. Gruener.

The authors gratefully acknowledge Doug Craig of the Exploration Systems Mission Directorate Integration Office (DIO) and Pat Troutman of LaRC supporting the DIO; Chris Moore of the ESMD Advanced Capabilities Division (ACD), and Frank Peri and Dave Beals of the Exploration Technology Development Program (ETDP) who support ACD; and Stephen Prusha, who manages the System Modeling and Analysis Program Office, under whose auspices this work was conducted. To all listed above, the authors express their appreciation for graciously contributing resources, analytical review and critique, and advocacy for this effort.

Some of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.